Edge-Based 3D Y/C Separation Using Wavelet Transform and Motion Compensation

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Abstract — *We propose new 3D adaptive Y/C separation algorithm for the composite video signal decoding. The exact calculation of the similarity is one of the key issues for the Y/C separation. We propose new approaches for the composite video signal decoding: 1) the use of the wavelet transform of the composite video signal for effective similarity computation, 2) an edge-based separation by using the composite video signal directly for sharp-edged results, 3) a simple motion-compensated similarity computation between frames. Also, the proposed algorithm has an adaptive architecture with which multiplication coefficients are adjusted by the similarity values between two pixels in lines of a field, two consecutive fields, and two consecutive frames. In case of comb failure, the proposed scheme resorts to the traditional band-pass filtering method. The experimental results show that the proposed method provides better performance than that of the conventional Y/C separation algorithms.*

Index Terms — comb filtering, composite video signal, Y/C separation, wavelet transform.

I. INTRODUCTION

HOME gateways or set-top boxes for home entertainment take multimedia signals entering a house and distribute them to television sets or computers [1]. It performs important functions such as record, conversion, and distribution of multimedia signals. For example, received composite video signals from TV broadcasting stations can be decoded for a television receiver, or can be recoded into a VCR. The recorded composite video signals can be converted into the progressive format for PC monitors or HDTV display terminals. For all those requirements, we need the process of conversion called composite video signal decoding.

The composite color video signal standards [2], [3] such as NTSC, PAL, and SECAM have been widely used for TV broadcasting systems due to its compatibility with the back and white TV and efficient transmission bandwidth usage. In the composite video signal, a quadrature modulation is applied to the chrominance signals (C) by a 90^o phase shift between two components of chrominance portion, and then, overlapped at the high frequency range of the luminance signal (Y). The phase shift of subcarriers between two consecutive interlaced scan lines in a field is 180^o.

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A receiver separates this composite signal into luminance and chrominance. The complete separation of Y/C at the decoder is virtually impossible, since the Y and C signals are overlapped and transmitted at the encoder. Many methods have been proposed for the effective Y/C separation of the composite color video signals [2]-[10]. The existing Y/C separation methods can be grouped into the following categories: simple analog filtering method, nonadaptive line comb filtering method, 2D adaptive filtering method, and 3D motion adaptive filtering method.

The oldest and simplest Y/C separation method is to split the composite video signal into Y and C signal with an analog low-pass or notch filter and a band-pass filter [2]-[3]. This technique utilizes that the color information is overlapped with the Y signal in a frequency band centered at subcarrier frequency. Since the filtered Y signal does not contain higher frequency Y signal components, fine details can be lost. The C information is not completely filtered out of the Y signal. Therefore, this method creates cross-luminance and cross-color artifacts [3]. This method is used for low-cost TV monitors and VCRs [4].

The simple nonadaptive line comb filtering method [2]-[4] uses two scan lines, the current scan line and the previous scan line. Y and C signals are obtained by adding the two lines together and by subtracting them with fixed multiplication coefficients, respectively. The shape of frequency responses of these processes looks like the teeth in a comb, so the name of the comb filtering. This technique is theoretically perfect when two scan lines have the same color components, since the phase of the C signals in the two scan lines is shifted by 180^o. The nonadaptive line comb filter improves the poor horizontal resolution and cross-luminance effects of the analog filter separation technique, however, it can not completely avoid cross-color artifacts when fine diagonal lines are presented in the picture.

In order to reduce the artifacts inherent in the nonadaptive comb filtering methods, the 2D adaptive comb filtering method [5]-[6] has been developed. This method adaptively adjusts the multiplication coefficients of every pixel of each line before the comb filtering. This method compares the composite video signals between the horizontal scan lines vertically for calculating the multiplication coefficients. In case of comb failure where the signals in the two lines are not similar, the conventional band pass filter can be used. This method produces better image quality than that of the nonadaptive line comb filter. However, images with very fine details that lack vertical correlation can not be separated completely.

The 3D adaptive comb filtering method known as a spatio-temporal approach is a near perfect technique currently

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available for the Y/C separation. This method adds motion information to the 2D adaptive comb filtering method. This method uses several video frames to decide the presence of motion: if there is no motion, the line comb filter is applied to the same location of the reference video frame and the searching video frame, otherwise, the 2D adaptive comb filter is employed within the current field. Therefore, this method creates perfect separation result when there is no motion between lines in consecutive frames.

With the trend of higher picture quality, various motion adaptive 3D comb filtering methods have been introduced for high-end TV receivers and VCRs [7]-[10]. The main concerns in [7] are the reduction of the frame memory size for LSI chip implementation. This method writes only samples of the effective area of the picture in the frame memory and only uses the chrominance bandwidth for the 3D Y/C separation at the expense of additional demodulator and modulator. A 3D Y/C separation filter is designed as a nonseparable filter in temporal-vertical frequency plane cascaded by 1D horizontal band-pass filter in [8]. The main design goal in [8] is to reduce the memory size for the Y/C separation by using a nonseparable filter design and to find the optimal filter coefficients by using a linear program. However, the adaptive nature of the video signals is not considered for the design of the filter. A motion adaptive 3D Y/C separation scheme [9] compares the frequency components of the composite video signals by using the fast Fourier transform (FFT) in order to determine the multiplication coefficients of the surrounding lines. This decoder can provide better separation result than that of the conventional time-based 3D Y/C separation methods, since both magnitude and phase characteristics of the composite video signals can be utilized. In [10] the motion estimation and compensation algorithms commonly used in the video coding techniques are employed to acquire more accurate motion information for the 3D Y/C separation. Even though this method is computationally complex, it provides better video quality in a moving region.

With the advances in VLSI technology, the most current methods of the Y/C separation of the composite video signals use the 3D adaptive comb filtering method which needs lager memory and an additional processing of motion information between frames. Most of 3D adaptive methods [7]-[10] compare lines in time-domain to compute multiplication coefficients for comb filtering. This method is simple to implement, however, may not provide better image quality than that of the transform-based method, since the characteristics of the composite video signals for the calculation of similarity between lines can be captured well in a transform domain, especially at noise environment. The use of Fourier transform [9] in the composite video decoding does not work well for a nonstationary signal like the composite video signal, and provides only global aspect of a signal. Also, the Fourier transform needs complex multiplications which cause to increase the computational complexity. Motion detection or motion-compensated approach is used for the motion similarity computation. Motion-compensated approach is more complex than motion detection method, since motion-compensated approach needs block-based motion estimation and compensation processes to find the best matched position. The use of the 2×2 decoded pixels after performing 2D Y/C separation of both fields [10] increases the complexity and decreases the speed of the 3D Y/C separation.

In this paper, we propose an edge-based 3D Y/C separation algorithm which adapts the wavelet transform [11]-[12] of the composite video signals, edge-based comb filtering, and a simple motion compensated 3D Y/C separation without the use of decoded images. The proposed method can produce faster and higher quality video than that of the existing 3D Y/C separation methods, since the proposed method utilizes the advantages of the wavelet transform over the Fourier transform, edge-based comb filtering, and faster motion compensation.

Section 2 introduces the details of the proposed algorithm. Experimental results and discussion are shown in Section 3, and concluding remarks are given in Section 4.

II. PROPOSED Y/C SEPARATION ALGORITHM

The flow chart of the proposed algorithm is shown in Fig. 1. The composite video signals are scanned in the interlaced form and are transmitted in fields.

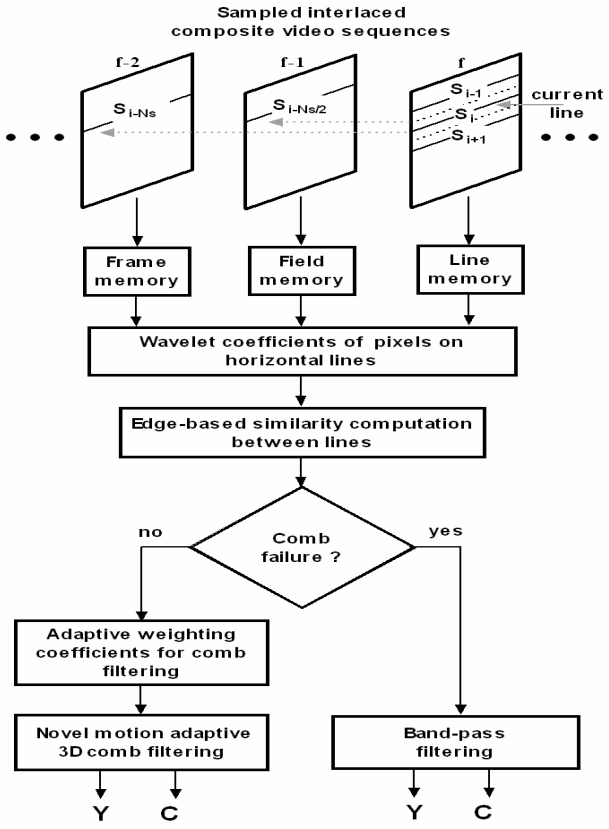

Fig. 1. The flow of the proposed algorithm.

Let *f, f-1, f-2* and N_s be the current filed, previous filed, previous frame, and the number of scanning lines in a frame, respectively. Pixels in the four lines stored in the memory, S_{i-1},

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S_{i+1}, $S_{i-Ns/2}$, and S_{i-Ns} are used for the Y/C separation of the current line, S_i. Wavelet transforms are applied for the current line and all the other four lines. The wavelet transform efficiently represents multiresolution aspects of a nonstationary signal like the composite video signals and does not need complex multiplications needed in FFT. The results of the wavelet transforms are compared in pixel bases for similarity computation which is used for multiplication coefficients of comb filtering. In order to find the best matched position and enhance sharpness along edges in decoded video, edges are considered in this step. For 3D Y/C separation, a similarity computation based on simple motion estimation is performed. In case all the similarities are very small, that is, comb failure situation, the proposed method resorts to the conventional band-pass filtering for more stable Y/C separation. The details of the algorithm are described in the following subsections.

A. Basics of the composite video signal

To aid in the understanding of the Y/C separation, the encoding of a composite video signal is briefly discussed. The luminance and the quadrature amplitude modulated chrominance information are added during encoding of the composite video signal. For example, the NTSC composite video signal is given as follows:

$$S(t) = Y(t) + Q(t)\cos(2\pi f_{sc} t + 33^\circ) - I(t)\sin(2\pi f_{sc} t + 33^\circ), \quad (1)$$

where, $Y(t)$, $Q(t)$, and $I(t)$ are the luminance component, the I component, and the Q component of the chrominance portion of the composite video signals, respectively. f_{sc} is the subcarrier frequency. As expressed in (1), chrominance signals are modulated using the quadrature amplitude modulation (QAM). As shown in Fig 2, the modulated C signal in the NTSC composite color video signal is overlapped on the high frequency of Y signal.

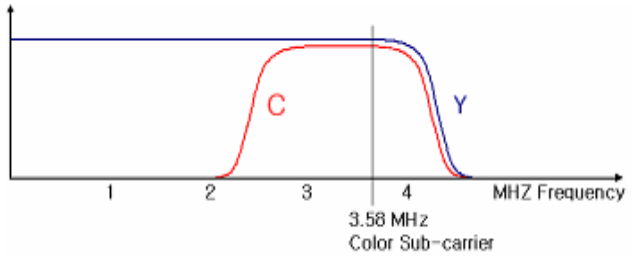

Fig. 2. Frequency spectrum of NTSC composite video signals.

There are 525 lines in a frame which is transmitted with odd and even field in interlaced form. The subcarrier frequency in the NTSC has been selected to be 227.5 times the horizontal line frequency. Therefore, the subcarrier phase at each point in one line will be 180 degrees away form the subcarrier phase at the same point in the previous line and following line. This encoding scheme makes the decoding of the composite video signal simple, since only simple addition and subtraction are needed for the perfect separation of the luminance and chrominance components in case an image contains no vertical frequency. However, real-life images have frequencies in various directions. Therefore, we need to find an efficient way of the Y/C separation reducing the visual artifacts in the decoded image.

B. Similarity computation using wavelet transform

The proposed algorithm uses the pixels in the current line, S_i and the four neighboring lines, S_{i-1}, S_{i+1}, $S_{i-Ns/2}$, and S_{i-Ns} in order to get higher chance of comb success. Note that the subcarriers of the four surrounding lines in Fig. 1 are out of phase from the subcarrier of the current line.

As shown in Fig. 3, wavelet transforms are performed for all the composite video signals of the current line and neighboring lines. Since chrominance information is overlapped on the higher frequency of luminance information in the composite video signals, wavelet packet decomposition is applied for only the higher frequency part which is a subtraction result from the original signal to low-pass filtered signals ($L_i(n)$). After N-level wavelet decomposition, the higher frequency signals ($H_i(n)$) are divided into signals of 2N subbands.

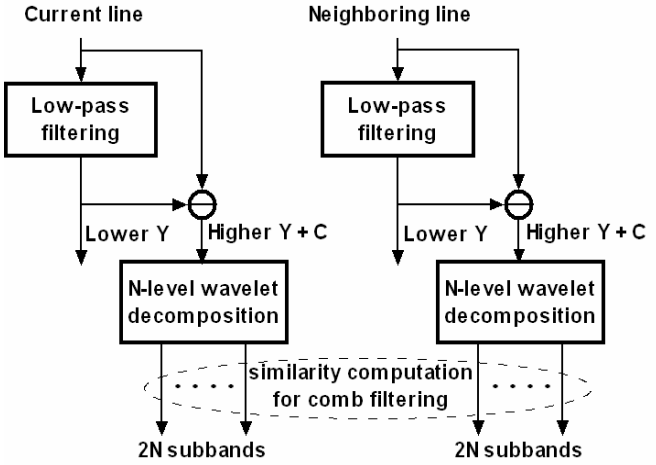

Fig. 3. Wavelet decomposition of the composite video signals.

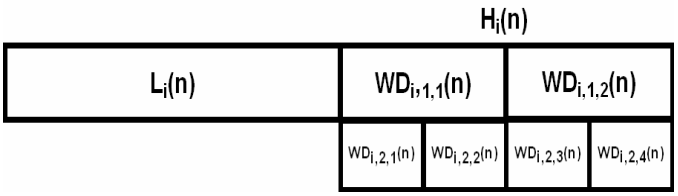

Fig. 4. Two-level wavelet decomposition of the composite video signals in a line *i* of a field *f*.

As an example, two-level wavelet decompositions of the current line and neighboring line are shown in Fig. 4. $L_i(n)$ and $H_i(n)$ are the low-pass and high-pass filtered outputs corresponding to a pixel position n of line i,

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respectively. For the Y/C separation, the similarity is computed using (2).

$$Y_{HSim(i,j)}(n) = \sum_{l=1}^{N} \left| WD_{i,l,k}(n) - WD_{j,l,k}(n) \right|,$$
$$C_{Sim(i,j)}(n) = \sum_{l=1}^{N} \left| WD_{i,l,k}(n) + WD_{j,l,k}(n) \right|, \; k = 1, \cdots, 2l \qquad (2)$$
$$Sim_{i,j}(n) = Y_{HSim(i,j)}(n) + C_{Sim(i,j)}(n),$$

where, $Y_{HSim(i,j)}(n)$, $C_{Sim(i,j)}(n)$, and $Sim_{i,j}(n)$ are similarity values of the high frequency of Y, C, and the composite video signal between lines i, and j at a position n, respectively. i and j are for the current line and the neighboring lines, respectively. l is a decomposition level, and $WD_{i,l,k}(n)$ are the wavelet decomposition results corresponding to position n of line i at level l. For example, when $l = 2$, $WD_{i,2,1}(n)$, $WD_{i,2,2}(n)$, $WD_{i,2,3}(n)$, and $WD_{i,2,4}(n)$ represent the signals corresponding position i at four different subbands. $Y_{HSim(i,j)}(n)$ and $C_{Sim(i,j)}(n)$ reflect the similarity values for luminance component and chrominance component of the composite video signals, respectively. If two compared signals are getting similar, and $Sim_{i,j}(n)$ becomes smaller.

C. Edge-based similarity computation

When there is motion between frames, the existing 3D Y/C separation methods filter the composite video signal vertically for 2D decoding. One of the disadvantages of those methods is that the decoded image signals may have visual artifacts [3] when an image contains horizontal edges or diagonal edges. Since human visual system is very sensitive to edges, an edge-based similarity calculation can create better image quality.

We can extract edges on the decoded image after Y/C separation in vertical direction, and then, do an edge-based comb filtering with a noninterlaced frame again. This two-step approach increases the processing delay, and the final results may contain the inherent separation errors occurred in the first step. In this paper, we propose a new approach which directly uses the composite video signals. Since Y and C information are overlapped and the color subcarriers are out of phase every other line, we can utilize the phase inversion characteristics of the composite video signals for the edge-based Y/C separation.

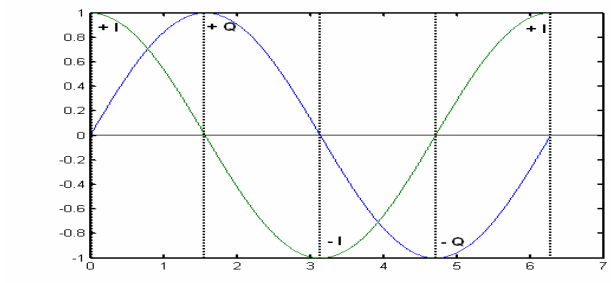

Fig. 5 Phase relationship of sampled NTSC signals.

As an example of $4f_{sc}$ sampling frequency, the chrominance components of the sampled NTSC signals in a line have a periodic sequences of +I, +Q, -I, and -Q. Since the subcarrier of the next line is out of phase from the current line, they are -I, -Q, +I, and +Q, respectively. Therefore, as shown in Table 1, the sampled NTSC signals around a current pixel position are as shown in Table 1.

Table 1. Sampled signals after 4fsc sampling.

Sequence / Line	n-2	n-1	n	n+1	n+2	n+3
i-2	**Y+I**	Y+Q	Y-I	Y-Q	**Y+I**	Y+Q
i-1	Y-I	Y-Q	**Y+I**	Y+Q	Y-I	Y-Q
i	**Y+I**	Y+Q	**Y-I**	Y-Q	**Y+I**	Y+Q
i+1	Y-I	Y-Q	**Y+I**	Y+Q	Y-I	Y-Q
i+2	**Y+I**	Y+Q	Y-I	Y-Q	**Y+I**	Y+Q

When a current comb filtering line and a sequence are i and n, respectively, the sampled signal is Y-I with $4f_{sc}$ sampling frequency. In this case, the sampled sequences which can be used for the comb filtering of the current position are the neighboring bold-styled (Y+I)s shown in Table 1. The other sampled signals have the same pattern. It can create better visual quality that the comb filtering is performed along the strongest edges. Note that the wavelet decomposition results of the sampled signals keep the same phase relationship as the sampled composite video signals shown in Table 1. The low-pass filtered output data of the current line are used for the edge extraction. The proposed edge-based comb filtering scheme is summarized as follows:

1) Calculate similarity values in vertical direction. If they are very similar, do the comb filtering in the vertical direction. Otherwise, go to step 2).
2) Extract horizontal edges in a local window centered at current position. If there are edges in the horizontal direction, compute the similarity values in horizontal direction. If they are very similar, do the comb filtering in the horizontal direction. Otherwise, go to step 3)
3) Extract the diagonal edges. If there are edges in diagonal direction, compute the similarity values in diagonal direction. If they are very similar, do the comb filtering in the diagonal direction. Otherwise, do comb failure processing as discussed later in this section.

Also, more details of the 3D adaptive comb filtering method will be described in Section 2.E.

D. Motion- compensated similarity computation

When there is no motion between frames, the original two video signals have the same Y and C information spatially. The 3D Y/C separation methods utilize this property: when there is no motion, the comb filtering is done by using the

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signals in two different frames, otherwise, a 2D comb filtering is done.

In general, motion detection is done by subtracting low-pass filtered Y signals or decoded Y signals at the same sequence numbers between two frames. This is simple to implement. However, the detected motion may be not accurate, since it ignores the C signals which are out of phase. Recently, the motion estimation and compensation method [10] which finds the best matching block in the previous frame was proposed for increasing the chance of comb success: this method increases the quality of the decoded image at the expense of complexity by using only 2D decoded Y signals for motion estimation.

We propose a simple and fast motion-compensated scheme which directly uses the wavelet decomposition results of both Y and C components of the sampled composite video signals. We use an $N \times 1$ block of a current position in the current line as a reference. The number of block matching with search blocks is limited to a predefined value of p. The proposed method takes following steps:

1) Start to calculate a similarity value between the reference block (the shadowed block in Fig. 6.a) and the search block. If the similarity value is smaller than a given threshold, stop the block matching and use the value of this search block for the comb filtering. Otherwise, go to step 2).
2) Compute a similarity value by moving a search block in spiral manner. If the similarity value in a search block during the block matching process is smaller than a given threshold, stop the process and use the value of this search block for the comb filtering. Otherwise, go to step 3).
3) Repeat the step 2) until the number of the block matching reaches to p. If there is no matched search block, the proposed Y/C separation method resorts to a 2D comb filtering.

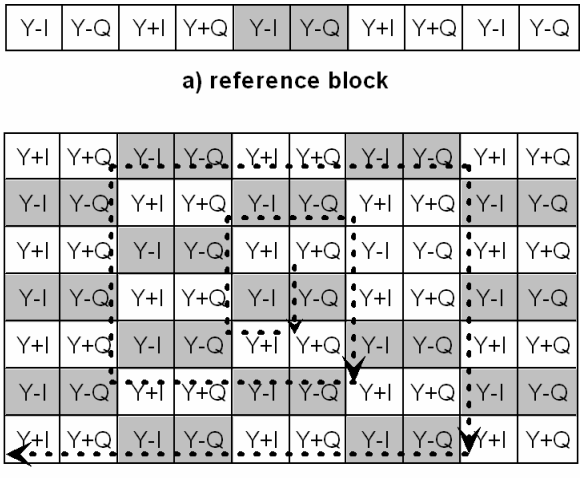

Fig. 6 Block matching process for the motion-compensated similarity calculation.

Fig. 6 illustrates the proposed method when the block size is 2×1. Most of conventional block methods for video compression use the raster scan order to the best matching block in an entire search range. Since the purpose of the block matching in this paper is not video compression but the similarity computation for the Y/C separation, we adapt the spiral scanning order and stop the block matching process whenever the similarity value is smaller than a given threshold: This can increase the speed when the two consecutive frames have small motion.

E. Adaptive comb filtering

The principle of the adaptive comb filtering is that multiplication coefficients of the comb filtering are larger (smaller) when the compared neighboring samples are getting similar (different) with a current sample. For example, when two compared samples in lines i and $i-1$ at position n are perfectly the same, the luminance value and the chrominance value are separated by (3), where the multiplication coefficient, $c_{i,i-1}(n)$ is 1.

$$Y_i(n) = L_i(n) + \frac{H_i(n) + c_{i,i-1}(n) \cdot H_{i-1}(n)}{2}, \qquad C_i(n) = \frac{H_i(n) - c_{i,i-1}(n) \cdot H_{i-1}(n)}{2}. \tag{3}$$

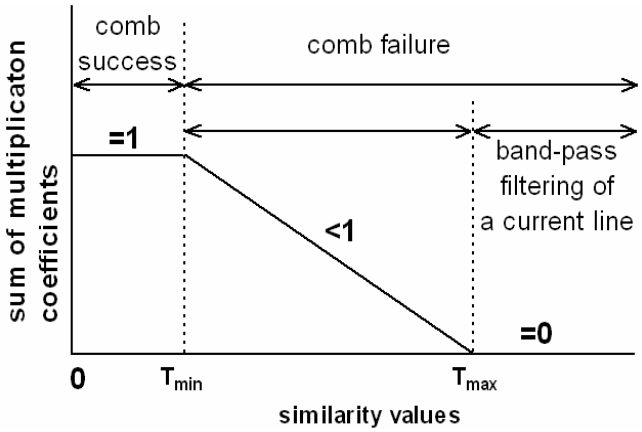

Fig. 7 Adaptive comb filtering scheme.

The proposed adaptive multiplication coefficient calculation scheme is illustrated in Fig. 7 and its corresponding equations are expressed in (4) ~ (8).

$$InvSim_i(n) = \sum_{j \in Neig} \frac{1}{Sim_{i,j}(n)}, \tag{4}$$

$$c_{i,j}(n) = \begin{cases} \dfrac{1}{InvSim_i(n)} \dfrac{1}{Sim_{i,j}(n)}, & if\ Sim_{i,j}(n) < T_{\min}, \quad (5.a), \\ \dfrac{1}{InvSim_i(n)} \dfrac{1}{Sim_{i,j}(n)} \dfrac{T_{\max} - Sim_{i,j}(n)}{T_{\max} - T_{\min}}, & if\ T_{\min} \le Sim_{i,j}(n) \le T_{\max}, \quad (5.b), \\ 0, & otherwise \quad (5.c), \end{cases}$$

$$sc_i(n) = \sum_{j \in Neig} c_{i,j}(n), \tag{6}$$

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Since a multiplication coefficient, $c_{i,j}(n)$ is inversely proportional to the similarity value, $Sim_{i,j}(n)$, $c_{i,j}(n)$ is calculated using (4) and (5). $InvSim_i(n)$ in (4) represents the sum of all the inverse of similarities between neighboring positions.

The proposed Y/C separation method is expressed in (7) and (8). When all the similarity values are less than $T_{\min}$, the comb filtering is success and the sum of multiplication coefficients, $sc_i(n)$ in (6) is 1. If all the similarity values are greater than $T_{\max}$, the case of comb failure, the comb filtering is done by a traditional band-pass filtering of a current line, i.e., the lower frequency part of the composite video signals is assigned as the luminance and the high frequency part is assigned as the chrominance. In this case, since $c_{i,j}(n)$ in (5) and $sc_i(n)$ in (6) are all zero, only band-pass filtering results of a current line are used for the comb filtering as expressed in (7.b) and (8.b). When one of similarity values lies in between $T_{\min}$ and $T_{\max}$, the sum of the multiplication coefficients is less than 1. In this case, the traditional band pass filtering result is partially added as expressed in (5.b), (7.b), and (8.b).

$$Y_i(n)=\begin{cases} L_i(n)+\dfrac{H_i(n)+H_{i-Ns}(n)}{2}, & if\ c_{i,i-Ns}(n)\le T_{\min} \quad (7.a)\\ L_i(n)+\dfrac{\sum_{j\in Neig} c_{i,j}(n)H_j(n)+sc_i(n)H_i(n)}{2}+(1-sc_i(n))L_i(n), & otherwise, \quad (7.b)\end{cases}$$

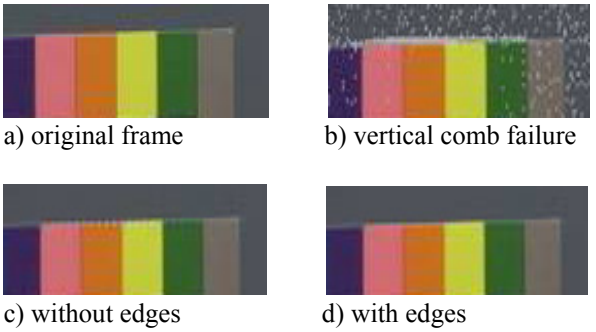
$$C_i(n)=\begin{cases} \dfrac{H_i(n)-H_{i-Ns}(n)}{2}, & if\ c_{i,i-Ns}(n)\le T_{\min} \quad (8.a)\\ \dfrac{\sum_{j\in Neig} c_{i,j}(n)H_j(n)-sc_i(n)H_i(n)}{2}+(1-sc_i(n))H_i(n), & otherwise, \quad (8.b)\end{cases}$$

When a motion similarity value $c_{i,i-Ns}(n)$ is less than $T_{\min}$, the proposed method relies only on a comb filtering between two positions in frames as expressed in (7.a) and (8.a). It is because that they are spatially at the same position and causes to decrease artifact frequently happened in a 2D comb filtering. Note that $c_{i,i-1}(n)$ and $c_{i,i+1}(n)$ are calculated by the edge-based similarity described by Section 2.C and $c_{i,i-Ns}(n)$ is calculated by the motion-compensated similarity scheme described by Section 2.D.

III. Experimental Results and Discussion

The proposed method is compared with conventional 3D Y/C separation methods which are based on time-domain [3] and the FFT-based Y/C separation [9]. Three groups of NTSC composite video signals with $4f_{sc}$ sampling frequency are used for this experiment: group A (simple videos like *hall* image sequence), group B (complex videos like *flower garden* image sequence), and group C (very complex videos like *MIT* image sequence).

Similarity values are calculated by two level wavelet packet decomposition with a simple wavelet filter, two-tap Daubechies filter. A 5×5 window centered on a current position is used for the edge extraction, which inputs are the filtered outputs of the composite video signals: After many experiments, we found that edges of them follows real object boundaries of original colors. For simple edge detection, we threshold the differences of two consecutive values at each direction within the local window and find the strongest edge direction by choosing the smallest accumulated differences when they are above the threshold. For more exact edge detection, more complex methods like [13] can be used.

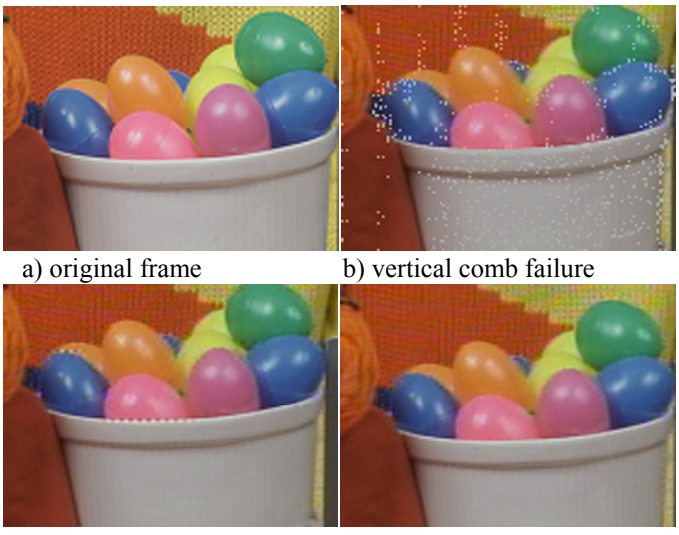


a) original frame b) vertical comb failure

c) without edges d) with edges

Fig. 8 An example of the edge-based Y/C separation.

Fig. 8 shows an effectiveness of the edge-based Y/C separation. The white dots in Fig. 8.b) show the pixel positions of vertical comb failures. If the Y/C separation is done only in the vertical direction, the artifacts are occurred along the edges as shown in Fig. 8.c). As shown in Fig. 8.d), the edge-based Y/C separation generates image quality much closer to the original image.



a) original frame b) vertical comb failure

c) without edges d) with edges and motion

Fig. 9 An experimental result of the proposed method.

Fig. 9 also shows an experimental result of the proposed Y/C separation method. As shown in Fig. 9.d), the proposed method which combines edge information and motion compensated similarity computation can reduce artifacts generated by conventional methods.

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Table 2. PSNR comparison.

	Group A	Group B	Group C
Time- domain [3]	27.49	26.71	24.83
FFT- based [9]	37.01	30.41	27.45
Proposed	39.15	32.60	29.40

Table 2 shows the average PSNR comparison results of the proposed method with other approaches when the edge-based and motion-compensated schemes are included. The results show that the proposed method generates higher quality than the existing methods. Therefore, the proposed algorithm can be applied to the Y/C separation for high-end NTSC video systems.

IV. CONCLUSION

In this paper, we proposed new adaptive Y/C separation algorithm for the composite video signal decoding. The proposed method combines edge information and simple motion compensated scheme by which the high quality decoded signal can be generated for the application of high-end NTSC systems. For more exact calculation of the similarity for adaptive weighting for Y/C separation, we used the wavelet transform of the composite video signal. The experimental results show that the proposed method provides better performance over the conventional Y/C separation algorithms in terms of decoded image quality. Especially, the proposed method creates sharper image around object boundaries which are very sensitive to human visual system.

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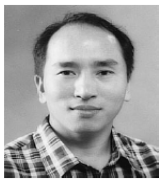

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